APPLICATION

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TITLE: COMPACT PROGRAMMABLE PHOTONIC VARIABLE DELAY DEVICES

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~~COMPACT PROGRAMMABLE PHOTONIC VARIABLE DELAY DEVICES~~

This invention was made with Government support under a Contract awarded by NASA, and is subject to the provisions of Public Law 96-517 (35 U.S.C 202) in which the inventor is granted right to retain title. The government has certain rights in this invention.

FIELD AND ORIGIN OF INVENTION

This invention pertains generally to the precision optical path length control, specifically to a photonic variable true time delay device for steering phased array radar, for constructing a transversal filter, and for controlling the optical path in optical interferometry.

BACKGROUND AND SUMMARY OF THE INVENTION

Phased array antennas have the important ability of beam steering without mechanical actuators. This feature is highly desirable for applications such as spacecraft, air craft, and mobile platforms where size and mass are restricted. The direction of a microwave (or millimeter wave) beam radiated from a phased array antenna is generally controlled by the relative phase distribution of microwave signals emitted by regularly spaced radiating elements. For a phased array of a wide instantaneous bandwidth, adjusting only the relative phase is not sufficient and so a relative time delay adjustment of the radiating elements must be introduced to avoid the beam pointing error known as squint, which results from the modification of the antenna phase pattern with changing frequency.

Conventional electronic beam forming systems for generating and delivering the requisite time delay and phase information are generally bulky, lossy, inefficient, and of narrow bandwidth. On the other hand, photonic beam forming offers the advantage of high packing density, wide signal bandwidth, light weight, immunity to electromagnetic interference, and remoting capability via optical fiber. Consequently, it has been under intensive investigation in the past few years and many photonic beam forming systems have been proposed and demonstrated. Photonic beam forming network use a lightwave carrier for the electrical signals of the radiating elements of the phased array, and provides the necessary time delay and phase information for beam steering.

For airborne and space-based phased arrays operating at mm-wave frequencies (20 GHz and above), the arrays are usually two-dimensional and a large number of array elements, typically a few thousand, are used. This requires that the beam forming network be two dimensional and have a very high packing density. In addition, the beam forming network must be reversible so that it can be used for both antenna transmitting and receiving. Furthermore, the total delay achievable of the delay network must be sufficiently large so that the maximum scanning angle of the phased array is adequate. Finally, as will be shown later, the delay resolution (the minimum step of delay change) must be fine enough (much less than the wavelength of the signal) to ensure that the angular resolution of the beam scanning is sufficient.

None of the proposed photonic beam forming networks to date meet all of the above requirements. The operation frequencies of the beam forming networks based on acousto-optic modulators (E. Toughlian and H. Zmuda, "A photonic variable RF delay line for phased array antennas," J. Lightwave Technol., vol. 8, pp. 1824–828, 1990) are limited to below 5 GHz and suffer from poor delay resolution, and therefore not adequate for mm-wave phased arrays. Path-switching time delay devices based on guided wave optics (C. T. Sullivan, S. D. mukherjee, M. K. Hibbs-Brenner, and A. Gopinath, "Switched time-delay elements based on AlGaAs/GaAs optical wave-guide technology at 1.32 mm for optically controlled phased array antennas," SPIE Proceedings, vol. 1703, pp. 264–21, 1992) are complicated, and are characterized by high loss, high cost, poor delay resolution, and one-dimensional geometry. The free-space path-switching time delay device (N. A. Riza, "Transmit/receive time-delay beam forming optical architecture for phased array antennas," Appl. Opt., vol. 30, pp. 4594–4595, 1991) shown in FIG. 1A is a two dimensional device of high packing density, and operates at high frequency with sufficient total delay. However, as shown in FIG. 1B, the delay resolution of the device is limited by the size of the vertical dimension d of the two dimensional delay array and equals to 2dn, where n is the refractive index of the required polarization beam splitting cube. For a d of 10 cm and a n of 1.5, the resulting delay resolution is 30 cm and is much too large for mm-wave antennas. In addition, presently the path-switched true time delay has a non-optimized design, making it bulky, expensive, and difficult to manufacture.

Even for narrow bandwidth phased arrays where true time delay is not necessary, a compact, two dimensional, and programmable phase shifter with high phase-shift resolution is highly desirable. Such a phase shifter can reduce the size and weight, and increase the pointing accuracy of the phased array radar.

Another important application of two dimensional true time delay device is in transversal filters (B. Moslehi, K. Chau, and J. Goodman, "fiber-optic signal processors with optical gain and reconfigurable weights," Proc. 4th Biennial Department Of Defense Fiber Optics and Photonics Conf., McLean, Va. 1994, pp. 303–309 and D. Nortton, S. Johns, and R. Soref, "Tunable wideband microwave transversal filter using high dispersive fiber delay lines," Proc. 4th Biennial Department Of Defense Fiber Optics And Photonics Conf., McLean, Va., 1994, pp. 297–301). In such a filter, a microwave or mm-meter wave signal is splitted into many branches and then recombined after the signal in these branches experiences different delays. For a certain set of delays, only the signal with a right frequency will add in phase and exit the beam combining junction with minimum loss. Other frequencies will destructively interfere and suffer severe loss—a bandpass filter is formed. By changing the delay arrangements, the center frequency of the pass band will also change, creating a dynamically tunable filter often referred to as transversal filter. Studies indicate that the bandwidth of the filter is inversely proportional to the number of branches and the frequency tuning resolution is proportional to the delay resolution of the branches. Therefore, a compact, two dimensional, and programmable true time delay with high delay resolution is ideal for constructing such a filter.

Yet another application of a variable delay line with high delay resolution is in optical interferometry, and in auto- and cross-correlation measurements of optical pulses. Presently, variable delay is accomplished by the combination of various forms of mechanical translation and is fine tuned by piezoelectric transducer. Because such a delay line involves mechanical moving parts, it is generally bulky, heavy, difficult to align, and less reliable. In addition, because the piezo-electric transducer suffers from hysteresis and temperature dependent drift, active control using feedback servo loop is required, resulting in a complicated system.

OBJECTS AND ADVANTAGES

Accordingly, it is an object of this invention to provide a two dimensional and variable true time delay device for phased array radar and for transversal filter applications. The device has the properties of high packing density, low loss, easy fabrication, fast delay variation, and virtually infinite bandwidth. The delay resolution of the device is sufficiently fine for accurate beam steering, and the total delay is adequately large to cover desired scanning angles. This device can be simplified to a phase-shifter beam former for phased arrays of narrow bandwidth, where true time delay is not necessary.

An other object of this invention is to provide a variable delay line which has no moving parts, no hysteresis, and no temperature dependent drift for applications in optical interferometry and optical pulse auto- and cross-correlationl measurements, and in other applications where a precision variable time delay is required.

Yet another object of this invention is to provide a manufacturing method for the mass production of the variable true time delay.

Further objects and advantages of this invention will become apparent from a consideration of the ensuring description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a schematic of a prior art path-switched variable delay device.

FIG. 1B shows that the delay resolution of the prior art two-dimensional path-switched variable delay device is limited by the vertical dimension of the device.

FIG. 2A shows the basic building block of an embodiment of this invention for improving the path-switched variable delay device.

FIG. 2B shows the polarization rotator array for controlling the state of polarization in each channel.

FIG. 2C is a cross section view of the basic building block, showing two different optical paths.

FIG. 2D shows an injection molded building block with pockets molded for different components.

FIG. 3A shows a ladder-structured variable delay device by stacking many basic building blocks on top of each other.

FIG. 3B shows a binary ladder-structured variable delay device that requires fewer basic building blocks.

FIG. 3C shows a scheme to allow the ladder-structured variable delay device to operate in both directions.

FIG. 4A is a bottom view of the variable delay device of FIG. 3, showing that packing more channels in the horizontal direction worsens the delay resolution of the device.

FIG. 4B shows a one dimensional ladder-structured variable delay device.

FIG. 4C shows packing many one dimensional ladder-structured variable delay devices together creates a two dimensional device with high packing density and good delay resolution.

FIG. 5A shows a basic unit of an index-switched variable delay device.

FIG. 5B shows a single channel of an index-switched variable delay device.

FIG. 5C shows a single channel of an index-switched binary variable delay device.

FIG. 6A shows a two dimensional construction of an index-switched variable delay device.

FIG. 6B shows a two-dimensional binary construction of an index-switched variable delay device.

FIG. 6C shows a tunable transversal filter constructed using a two dimensional index-switched variable delay device.

FIG. 7A shows a first implementation to allow the index-switched variable delay device to operate in both directions.

FIG. 7B shows an alternative implementation to allow the index-switched variable delay device to operate in both directions.

FIG. 8 shows cascading an index-switched two dimensional delay device with a ladder-structured two dimensional delay device.

FIG. 9 shows a zig-zag construction of an index-switched variable delay device.

FIG. 10A is a cross section view of the zig-zag construction of the index-switched variable delay device.

FIG. 10B shows a 4f arrangement of the lenses used to overcome diffraction.

FIG. 10C is another cross section view of the zig-zag construction of the index-switched variable delay device.

REFERENCE NUMBERS IN DRAWINGS

20	Optical beam
20A	Reverse direction optical beam
22	90° polarization rotator array
24L	Left Polarization Beamsplitter (PBS)
24R	Right PBS
26	Corner reflector
27A	Horizontal polarizer
27B	Vertical polarizer
28L	Left polarization rotator
28R	Right polarization rotator
30A	Horizontal Polarization
30B	Perpendicular polarization
32	Switch
34	Control signal
36	External polarization rotator
38L	Left external PBS
38R	Right external PBS
40	Birefringent crystal
42	Polarization rotator
44	Electrodes
46	Laser array
48	Microwave signal
50	Photodetector array
52	Laser source
54	Collimating lens
56	Grid amplifier
58	Radiating microwave beam
60	Electrical signal combiner
62	Left laser array
64	Left collimating lens array
68L	Left external polarization rotator array
68R	Right external polarization rotator array
70	Left focusing lens array
72	Left photodetector array
74	Right focusing lens array
76	Right photodetector array
78	Left collimating lens array
80	Right diode laser array
82	Focusing lens
84	Photodetector
86A	Upper corner reflector array
86B	Lower corner reflector array
88A	Upper lens array
88B	Lower lens array
90A	Upper polarization rotator array
90B	Lower polarization rotator array
92	Birefringent crystal slabs
94	Voltage
96	Microlens
98	Insulating layers

DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to FIG. 2A, the basic building block of a ladder-structured variable delay unit of this invention con-

sists of a polarization rotator array **22**, two polarization beamsplitters (PBS) **24L** and **24R**, an optional horizontal polarizer **27A**, and an optional vertical polarizer **27B**. Polarization rotator array **22** is shown in FIG. **2B** and it may comprise of liquid crystal polarization rotators, magneto-optical polarization rotators, or electrooptical polarization rotators. In the array, each pair of rotators **28L** and **28R** defines a signal channel and can be independently controlled. The pair should always be in the same state. For example, rotators (B,j) and (B,j') in FIG. **2B** should be "on" or "off" simultaneously, where j and j' are coordinate integers. All channels in the block share the same polarization beamsplitters and polarizers. As shown in FIG. **2C**, when a switch **32** and a control signal **34** activate a polarization rotator **28L**, a horizontal polarization state **30A** of an incoming light beam **20** is rotated 90 degrees to a perpendicular polarization **30B**, causing the beam to be reflected by polarization beamsplitters **24L** and **24R**, and going toward the output. After passing a corresponding polarization rotator **28R** at the output side, polarization state **30B** of beam **20** is rotated back to polarization state **30A**. The block is called in "reflecting state." On the other hand, when switch **32** and control signal **34** de-activate polarization rotator 28L, polarization state **30A** of beam **20** is unchanged and the beam will pass polarization beamsplitter **24L**, going toward another basic building block. The block is called in "passing state." The optional polarizers **27A** and **27B** can be used to minimize the polarization cross-talk between the "reflecting state" and the "passing state."

To lower manufacturing cost, each building block can be injection-molded using glass, acrylic, or other types of materials. As illustrated in FIG. **2D**, slots for polarization beamsplitters **24L** and **24R**, polarizers **27A** and **27B**, and polarization rotator array **22** are pre-molded on a glass (or plastic) block. When the unit is assembled, polarization rotator array **22**, polarization beamsplitters **24L** and **24R**, and polarizers **27A** and **27B** can be simply dropped into the slots and then affixed in the slots using some epoxy that is index-matched to the building block. To further decrease the optical loss caused by the attenuation of the molding material, the optical path of each channel can be made hollow. This injection molding process is especially important for mass-production of the delay units.

The ladder-structured variable delay device is constructed by stacking multiple basic building blocks on top of each other, as shown in FIG. **3A**. Whenever the beam encounters a basic block in reflecting state, it will be directed toward the output. For example, if the ith block is in reflecting state but all the blocks before it are in passing state, the total delay ΔL of the unit is

$$\Delta L=2(i-1)nh, \tag{1}$$

where n and h are the refractive index and height of the basic building block respectively. The smallest delay increment is thus.

$$\Delta l=2nh \tag{2}$$

Because the delay unit closely assembles a ladder, the structure of the delay unit is referred to as "ladder" construction. This structure is more compact than that of the conventional path switched delay shown in FIG. **1**. The ladder structure is more suited for mass production and therefore less expensive to manufacture.

To minimize the number of basic building blocks used in a ladder-structured variable delay device, the basic building blocks can be arranged in a binary fashion such that the distance between two consecutive blocks increases by a factor of 2, as shown in FIG. **3B**. Let M be the total number of the blocks used (or bits), then the maximum value of the delay generated is:

$$\Delta L_{max}=(2^0+2^1+2^2+\ldots 2^{M-1})\,\Delta l=(2^M-1)\Delta l \tag{3}$$

where Δl=2nh is the smallest delay increment. By properly adjusting the polarization state of the light beam in each block, any time delay in the range from Δl to ΔL_{max} can be obtained with a resolution (or delay increment) of Δl.

The ladder-structured variable delay device can be made to operate bidirectionally by placing an external polarization beamsplitter **38L** at left end of the device, another external polarization beamsplitter **38R** at right end of the device, and an external large area polarization rotator **36** covering both the left and right ends, as shown in FIG. **3C**. For left to right operation, an optical beam **20** having a horizontoal polarization **30A** enters the device from left external polarization beamsplitter **38L**. External polarization rotator **36** is de-activated to allow optical beam **20** passing through left external polarization beamsplitter **38L** and entering the delay device. On the other hand, for right to left operation, an optical beam **20A** having a perpendicular polarization **30B** enters the device by reflecting off right external polarization beamsplitter **38R**. External polarization rotator **36** is activated to rotate perpendicular polarization **30B** to horizontal polarization **30A** before entering the device. When optical beam **20B** reaches the left side of the delay device, external polarization rotator **36** automatically rotates horizontal polarization **30A** back to perpendicular polarization **30B** so that optical beam **20A** exits the delay device by reflecting off left external polarization beamsplitter **38L**.

FIG. **4A** is a bottom view of the ladder-structured delay device described above and the delay resolution is limited by the horizontal dimension d_1. To improve the delay resolution, d_1 should be reduced. The minimum d_1 equals to twice of the beam size of the light beam, at which the number of channels in the horizontal direction reduce to one, as shown in FIG. **4B**. Consequently, the 2-D delay device reduces to an 1-D delay device. However, many of such 1-D delays can be stacked together to form a high packing density of 2-D device, as shown in FIG. **4C**. Unlike the 2-D delay of FIG. **2**, the input and output channels are interlaced.

Accordingly, the ladder construction of this invention provides compactness and high packing density. The basic building block is simple and the complete unit consists of many basic building blocks that are stacked together. In addition, two or more units can be cascaded to further increase delay range. Because liquid crystals are used to control the relative delay of each channel, both control voltage and power consumption are low. By injection molding the structure of the device with glass or plastic, the fabrication cost can be greatly reduced. Because the passing states and the reflecting states have orthogonal polarizations, high delay isolation (defined as the optical power of wanted delay divided by the optical power of unwanted delay) is readily achievable with the insertion of polarizers. Finally, the optical loss of the device is low.

The delay resolution of the path switched delay described above is not fine enough for millimeter waves applications, where the delay resolution must be much less than 1 mm. The following describes an index switched variable delay device for achieving high delay resolution for mm wave and other applications where high delay resolution is required.

FIG. **5A** shows the basic unit of the index-switched variable delay device. The basic unit consists of a birefringent crystal segment **40** cut along the principal axes (X,Y,Z)

of the crystal with the light beam propagating along the X axis (or Y axis). Input light beam **20** is polarized either in the Z direction or in the Y (or X) direction (the two principal directions of the crystal). The Y (or X) polarized beam experiences a refractive index of n_o and the Z polarized beam experiences a refractive index of n_e. If the polarization of the light beam is rotated 90°, it will experience a delay difference of $\Delta l=(n_e-n_o)l$, where l is the length of the crystal segment.

A delay line can be constructed by putting many such crystal segments together in a linear array, as shown in FIG. **5B**. A polarization rotator **42** is sandwiched between two neighboring segments to control the beam's polarization states. Polarization rotator **42** can be a liquid crystal, a magneto-optic, or an electro-optic element. It is evident from FIG. **5B** that the time delay of the beam can easily be altered by changing beam's polarization in each segment so that the refractive index the beam experiences will change. We call this method index-switching technique. To obtain even finer delay resolution, a pair of electrodes **44** may be placed across a birefringent crystal segment for applying an electrical field and changing the refractive index of the crystal via the electro-optic (or Pockel's) effect.

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~~To minimize the number of polarization rotators in the device, the lengths of the crystal segments increases successively by a factor of 2, as shown in FIG. 5C.~~ The relative optical path delay Δl between the two polarization states in the smallest segment of length l (the least significant bit) is

$$\Delta l=(n_e-n_o)l. \tag{4}$$

Let M be the total number of crystal segments (or bits), then the maximum value of the delay generated is:

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$$\Delta L_{max}=(2^0+2^1+2^2+\ldots 2^M-1)\ \Delta l=(2^M-1)\Delta l \tag{5}$$

?

By properly adjusting the polarization state of the light beam in each segment **40**, any optical path delay in the range from Δl to ΔL_{max} can be obtained with a resolution (or delay increment) of Δl. Because the length of each crystal segment **40** can be tightly controlled, the accuracy of the device can be very high.

Several delay lines of the design described above can be densely packed in two dimensions to form a compact variable delay device. However, instead of cutting crystal into narrow strips, large area crystal segments **40** and polarzation rotator arrays **22** (spatial light modulators) are used to construct the multiple channel delay device, as shown in FIG. **6**. Here polarization rotators in all polarization rotator arrays are aligned element by element and the size of each channel is determined by the size of the rotators. For 2 mm channel spacing, the packing density of the device is 25/cm². Such a channel spacing is easily attainable in practice, considering that a 1.4 mm diameter Gaussian beam with 1 μm wavelength has a Rayleigh range of 1.54 meters.

In FIG. **6A**, the input light beams are emitted from a diode laser array **46** with each laser beam collimated by a microlens. Lasers in laser array **46** are modulated by a microwave or RF signal **48**. At the output end, each beam will be focused to a photodector on a detector array **50** by a microlens in front of each phtotodetector. The photodectors will convert the optical signals into microwave or RF signals with proper delays between the channels encoded by the delay device. In FIG. **6B**, a single laser **52** is modulated by a microwave or RF signal **48**. The laser beam is then expanded by a lens **54** and passes through the delay device. At the output end, each microlens in front of each photodetector focuses the light in the corresponding channel to the corresponding photodetector on detector array **50**. The converted microwave or RF signals from all channels then incident on to a grid amplifier **56** and radiate away. The radiation angle of the resulting microwave or RF beam **58** is controlled by the relative delay relations between the delay channels.

FIG. **6C** shows a tunable transversal filter constructed by a two dimensional index switched variable delay device. In this filer, a microwave or millimeter wave signal **48** is used to modulate a laser **52**. The laser beam is expanded and passes through a two dimensional index switched variable delay device. Different portions of the beam defined by each element of the polarization rotator arrays will experience different delays. At the output end, each microlens in front of each photodetector will focus each corresponding portion of the beam to the corresponding photodetector on detector array **50** to convert the modulated light back to the microwave or mm-wave signal. All the microwave or mm-wave signals from all the photodetectors will be summed in an electrical signal combiner **60**. For a certain set of delays, only the signal with a right frequency will add in phase and exit the beam combining junction with minimum loss. Other frequencies will destructively interfere and suffer severe loss—a bandpass filter is formed. By changing the delay arrangements, the center frequency of the pass band will also change, creating a dynamically tunable filter. Because a large number of signal channels are densely packed together, the resulting filter has a narrow bandwidth. Because the delay resolution of the index switched delay device is high, the frequency tuning resolution is also high. In addition, the fast speed of changing the delay arrangement makes tuning the filter very fast. Similar tunable filter can also be constructed with a ladder-structured optical variable delay device described earlier.

The index switched delay device can be used for both transmitting and receiving operations. As shown in FIGS. **7A** and **7B**, for the bi-directional operation, an external polarization beamsplitter (PBS) **38L** and an external polarization rotator array **68L** are placed at the left hand side of the device. Similarly, a second external PBS **38R** and a second external polarization rotator array **68R** are placed at the right hand side. Laser beams from the left hand side are polarized in the plane of the paper and passes through left PBS **38L**. On the other hand, laser beams from the right hand side are polarized perpendicular to the plane of the paper and reflect off right PBS **38R**.

In FIG. **7A**, the left laser transmitter includes a left diode laser array **62** and a left collimating lens array **64** which collimates light from each laser diode. The left receiver includes a left photodetector array **76** and a left focusing lens array **74** which focus light from each channel to a corresponding photodetector on detector array **76**. Similarly, the right laser transmitter includes a right diode laser array **80** and a left collimating lens array **78** which collimates light from each laser diode on laser array **80**. The right receiver includes a left photodetector array **72** and a left focusing lens array **70** which focus light from each channel to a corresponding photodetector on left photodetector array **72**. In FIG. **7B**, the left laser transmitter contains only a single laser **52** and a collimating lens **54**. The left side receiver consists of a single detector **84** and a focusing lens **82** that focus light from all channels to the photodetector. The laser beams transmitted from the right laser array are assumed to be incoherent.

When in the transmitting mode, left external polarization rotator array **68L** is inactive. However, right external polarization rotator array **68R** is such programmed that it always

brings the polarization of light beams in each channel back to be in the plane of the paper after the delay device. This assures that light beams of all channels will pass PBS **38R** and be received by right photodetector array **76**. A left focusing lens array **74** is placed before left photodetector array **76** to focus light of each individual channel to a corresponding detector on left photodetector array **76**. When in the receiving mode, right external polarization rotator array **68R** is inactive. However, left polarization rotator array **68L** is such programmed that it always brings the polarization of light beam in each channel back to be perpendicular to the plane of paper after the delay device. This assures that all channels will reflect off PBS **38L** and be received by a detector array **72**, as in FIG. **7A**, or a detector **84** as in FIG. **7B**.

The same concept can also be used to make phase shifters for phased array antennas with narrow bandwidth where true time delay is not necessary. For example, an 8. GHz (X-band) carrier has a wavelength of 3.75 cm. To obtain a total phase shift of 2π for such a carrier, a total length of only 13 cm of Rutile crystal per channel is required. For a Ka band carrier of wavelength of 0.75 cm (40 GHz), only 2.6 cm Rutile crystal per channel is required.

TABLE I

	$n_o - n_e = \Delta l/l$	Crystal for 1 cm delay
Orpiment (As_2S_3)	0.4	2.5 cm
Geikelite ($MgTiO_3$)	0.36	2.78 cm
Tellurite (TiO_2)	0.35	2.86 cm
Prousite	0.29	3.45 cm
Rutile (TiO_2)	0.287	3.48 cm
Ag_3AsS_3	0.28	3.57 cm
Calcite	−0.172	5.81 cm
$LiNbO_3$	−0.086	11.63 cm
Quartz	0.0091	110 cm
PM Fiber	$\sim 6 \times 10^{-4}$	~1667 cm

Table I listed the birefringence of potential birefringent materials for fabricating the proposed delay lines. Note that different crystals may be used together to construct a delay line: a crystal with small birefringence can be used to make segments of small delays (less significant bits) and a crystal with large birefringence can be used to make segments of large delays (more significant bits).

The maximum delay ΔL_{max} required of a beam forming network of a phased array antenna with N×N elements is

$$\Delta L_{max} = (N-1)d_{max}\sin|\theta_{max}| = \frac{(N-1)\lambda\cdot\sin|\theta_{max}|}{(1+\sin|\theta_{max}|)} \tag{6}$$

where θ_{max} is the maximum beam scanning angle, λ is the wavelength of the carrier (microwave) signal of the phased array, and $d_{max}=\lambda/(1+\sin|\theta_{max}|)$ is the maximum array spacing allowed before higher order diffraction degrade the antenna gain.

To achieve an angular beam scanning resolution of $\Delta\theta$, the delay resolution or the minimum path delay between the two adjacent elements Δl is required to be

$$\Delta l = \frac{\lambda\cdot\cos\theta_{max}\Delta\theta}{(1+\sin|\theta_{max}|)}. \tag{7}$$

Table II lists the values of required maximum delay ΔL_{max} and delay resolution Δl for a phased array with λ=0.75 cm (40 GHz), N=64, and $\Delta\theta$=1°. The corresponding crystal lengths for the maximum and the minimum delays are also listed. For example, for the case of θ_{max}=30°, $LiNbO_3$ crystal of length 0.87 mm can be used to make the segment of the smallest delay of 76.5 μm and the Rutile crystal of the total length of about 55 cm can be used to make other larger delay segments that have a total delay of 15.75 cm. In the table, the number of bits M is calculated using $M=\log_2(1+\Delta L_{max}/\Delta l)$.

TABLE II

	θ_{max} = 5°	θ_{max} = 10°	θ_{max} = 30°	θ_{max} = 60°
ΔL_{max}	3.78 cm or 5.04 λ	7 cm or 9.33 λ	15.75 cm or 21 λ	21.93 cm or 29.24 λ
L_{max} (Rutile)	13.48 cm	24.4 cm	55 cm	76.4 cm
Δl	0.12 mm	0.11 m	0.0756 mm	0.035 m
l ($LiNbO_3$)	1.4 mm	1.3 mm	0.87 mm	0.41 mm
M No. of bits	7	8	11	12

It should be noted that Rutile has excellent optical and physical properties: it is transparent to light from 500 nm to 5 μm and its birefringence (n_e-n_o) remains almost unchanged from 430 nm to 4 μm. It has a density of 4.26 g/cm^3, a melting point of 2093° K., and a solubility in water less than 0.001.

To reduce the cost and to extend the delay range, the index-changing delay elements may be cascaded with a ladder structured path-switching delay device described previously, as shown in FIG. **8**. The birefringent crystal segments are used for the less significant bits of high delay resolution and the path switching concept is used for the more significant bits of large delays. This cascaded construction combines the advantages of both techniques and avoids their short comings. The total length of the crystal segments per channel is now reduced to few centimeters.

In stead of cutting crystals into many segments, the index-switching time delay unit may also be constructed using slabs of crystal, as shown in FIG. **9**. Such a unit consists of slabs of birefringent crystal **92**, a upper layer of polarization rotators **90A** (which may be individually and independently controlled), an optional lower layer polarization rotators **90B**, a upper row of corner reflectors **86A**, a lower row of corner reflectors **86B**, an optional upper lens array **88A**, and an optional lower lens array **88B**.

FIG. **10A** is a cross section view of the device. The crystal slabs are cut along the principal axes (X,Y,Z) of the crystal and light beam propagates along the X (or Y axis). The beam is polarized either in the Z direction or in the Y (or X) direction (two principal directions of the crystal). Similar to the linear construction described in FIG. **5**, here the polarization state of the light beam can also be easily switched between Y and Z direction by the 90° polarization rotators and the beam will experience n_o and n_e accordingly. Lenses **96** are used to overcome beam's diffraction and the distance between two consecutive lenses is $2f$, where f is the focal length of the lenses, as shown in FIG. **10B**. In this construction the height of the crystal determines the smallest delay (delay resolution) and the total number of paths determines the maximum delay. The spacing between the polarization rotators increase successively by a factor of 2 to make the delay line binary, as in FIG. **5**. As shown in FIG. **9** and FIG. **10C**, many crystal slabs may be stacked together to construct a one dimensional delay array. Compared with the linear construction of FIG. **5**, the zig-zag construction uses less crystal. However, it is inherently one dimensional and thus has a lower packing density than that of the linear construction.